Reading Acquisition Reorganizes the Phonological Awareness Network Only in Alphabetic Writing Systems

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Abstract: It is unknown how experience with different types of orthographies influences the neural basis of oral language processing. In order to determine the effects of alphabetic and nonalphabetic writing systems, the current study examined the influence of learning to read on oral language in English and Chinese speakers. Children (8–12 years olds) and adults made rhyming judgments to pairs of spoken words during functional magnetic resonance imaging (fMRI). Developmental increases were seen only for English speakers in the left hemisphere phonological network (superior temporal gyrus (STG), inferior parietal lobule, and inferior frontal gyrus). The increase in the STG was more pronounced for words with conflicting orthography (e.g. pint-mint; jazz-has) even though access to orthography was irrelevant to the task. Moreover, higher reading skill was correlated with greater activation in the STG only for English speaking children. The effects suggest that learning to read reorganizes the phonological awareness network only for alphabetic and not logographic writing systems because of differences in the principles for mapping between orthographic and phonological representations. The reorganization of the auditory cortex may result in better phonological awareness skills in alphabetic readers. *Hum Brain Mapp 34:3354–3368, 2013.*

Key words: spoken language; rhyming; Chinese; orthography; phonology; development; cross-linguistic; English

INTRODUCTION

The structure of writing systems may differentially reorganize phonological networks, leading to a growing divergence between different orthographies with increased experience. Orthographies, such as English, follow the alphabetic principle with semiregular mapping between graphemes (letters) and phonemes (sounds), thus leading to changes in the phonological network over the course of development. Conversely, nonalphabetic orthographies, such as Chinese, have phonetic radicals that offer some cues to syllabic level pronunciation, yet, do not have systematic mappings from character to syllable. As a result, nonalphabetic orthographies may not engage phonological representations to the same degree. Evidence from behavioral and imaging studies suggest that engagement of the

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phonological network during spoken word processing may be influenced by the structure of the orthographic system and lead to a growing divergence in the phonological network between alphabetic and nonalphabetic orthographies. However, no previous investigations have directly compared orthographic effects on spoken language processing between English and Chinese. Here we directly test potential differences between alphabetic and nonalphabetic orthographies by comparing spoken word processing using a phonological task (rhyming) in adults and children who can read English or Chinese.

Behavioral research shows that the interaction between orthographic and phonological representations varies across languages in adults. In English, written word processing is associated with strong involvement of phonology [Goswami, 1993; Nation and Hulme, 1997; Stahl and Murray, 1994; Wagner and Torgesen, 1987; Wagner et al., 1997]. Additionally, orthographic representations in alphabetic systems, i.e., English and French, influence spoken word processing [Perre and Ziegler, 2008; Ziegler and Ferrand, 1998]. In contrast, written word processing in Chinese is associated with weaker involvement of phonology [Zhou et al., 1999]. While English is associated with strong orthographic effects on spoken word processing, investigations of oral language processing in Chinese reveal a significantly weaker effect of orthography [De Gelder and Vroomen, 1992].

Behavioral research also shows that developmental changes in the reciprocal influence between orthography and phonology vary across languages. In alphabetic orthographies, phonological awareness strongly predicts later reading proficiency in early readers [Anthony and Lonigan, 2004; Ball and Blachman, 1991; Bradley and Bryant, 1983; Liberman et al., 1974; Muter et al., 1997; Nation and Hulme, 1997; Scarborough, 1998; Schatschneider et al., 2004; Wagner and Torgesen, 1987; Wagner et al., 1993, 1997]. Orthographic knowledge (e.g. letter names) is also a strong predictor of later phonological awareness [Wagner et al., 1997]. In fact, a developmental shift from awareness of larger (words and syllables) to smaller (letters) orthographic grain sizes [Anthony et al., 2003] may be driven by the nature of an alphabetic system. In Chinese, phonological awareness at the level of the phoneme is a weaker predictor of later reading proficiency [Newman et al., 2011]. In addition, early reading development in Chinese is characterized by sensitivity to larger grain size (characters correspond to syllables) and thus, reading skill is only weakly related to later phonological awareness [Newman et al., 2011]. Individuals who read Chinese who have also had exposure to an alphabetic system when learning to read (e.g. pinyin) show greater phonological awareness skills than those who have not [Cheung et al., 2001; Ho and Bryant, 1997; Huang and Hanley, 1994, 1997; Mc-Bride-Chang et al., 2004] which further supports the idea that sensitivity to smaller units, such as letters, influences the phonological network.

Converging neuroimaging and electrophysiological evidence suggests that orthography may influence oral language processing in adults who read alphabetic orthographies. Spoken language tasks have revealed activation in the FG, suggesting that orthographic representations are activated even during oral language [Booth et al., 2002]. Consistent with this, event-related potentials (ERPs) have shown that conflicting orthography and phonology are associated with early effects in spoken language processing that occur before semantic processes [Perre and Pattamadilok, 2009]. Transcranial magnetic stimulation (TMS) has also shown that the advantage for consistently spelled words during auditory lexical decision disappears when stimulation was delivered to inferior parietal cortex, but not to ventral occipital temporal cortex, indicating that the consistency effect arises at a phonological rather than an orthographic level [Pattamadilok et al., 2010]. In contrast to these findings in alphabetic languages, Chinese shows little evidence for the influence of orthography on oral language [Cao et al., 2011].

Neuroimaging research also suggests that the influence of orthography on spoken language processing increases with age and/or skill in alphabetic, but not nonalphabetic systems. Cone et al. [2008] examined spoken language processing using a rhyming task in children ages 9 to 15 years and found developmental increases in activation of left middle temporal gyrus (BA 22) and left dorsal IFG for conflicting (e.g. PINT-MINT) orthography. Increases in left IFG suggest an increased involvement for strategic phonological processing when orthography and phonology conflict. The same study revealed that the amount of activation in FG was correlated with reaction times especially for the older children [Cone et al., 2008]. Studies on children with reading disabilities have revealed less activation in FG during spoken word rhyming suggesting that lower skill is associated with weaker activation of orthographic representations during oral language tasks [Desroches et al., 2010]. Studies of the effects of literacy on phonological representations find that literates show greater activation than illiterates in IPL for words and greater activation in right IFG for pseudowords [Castro-Caldes et al., 1998]. Literates also showed greater activation than illiterates for words and pseudowords in STG and FG [Dehaene, 2010]. These results collectively suggest that increases in age and reading skill are associated with increased engagement of both orthographic and phonological regions during spoken language tasks in alphabetic languages. To date, research on the influence of orthography on phonological tasks in Chinese revealed a developmental decrease in FG and an early increase in STG [Cao et al., 2011]. These results suggest that Chinese characters may not have the same impact as alphabetic letters on recruitment of both orthographic and phonological regions during spoken language tasks; however, the conclusions that can be drawn from these separate studies of English and Chinese are limited in that they did not include a direct comparison of Chinese and English.

Although there has been extensive research examining developmental differences in reading in different languages [Ben-Shachar et al., 2011; Brem et al., 2010; Brown et al., 2005; Hoeft et al., 2011; Parviainen et al., 2006; Schlaggar and McCandliss, 2007; Turkeltaub et al., 2003], there is minimal research in spoken language processing [Cao et al., 2011; Cone et al., 2008]. The current study extends Cone et al. [2008] by including adults as well as children and extends Cao et al. [2011] by including a direct comparison of developmental changes in English and Chinese spoken word rhyming. Reorganization of auditory cortex may take time, so Cone et al. [2008] may not have found differences between younger and older children in left STG. By comparing adults with children, the current study can examine skilled automatic readers with years of experience to relatively novice readers. By directly comparing Chinese and English speaking children and adults, cross-linguistic differences can be ascertained in ways these two separate studies could not. Because the previous studies focused within language, any conclusions about cross-linguistic differences are speculative.

We sought to investigate how the nature of different writing systems (i.e., English and Chinese) influences the development of the phonological awareness network, with the expectation that orthographic information should influence the phonological network to a greater degree in English because learning English promotes strong associations between the visual letter forms and the phonemes they represent, whereas Chinese has weaker associations between orthography and phonology. Additional evidence for greater involvement of orthography in phonological awareness tasks for alphabetic languages would be shown by larger developmental differences in English for words with conflicting orthographic information (e.g. pint-mint, jazz-has) as compared with a similar manipulation of orthographic conflict in Chinese. The effect of conflicting orthographic information on a rhyming judgment in the auditory modality would be indicative of the influence of visual word forms on phonological awareness. Finally, we predict a stronger correlation between reading skill and engagement of the phonological awareness network in native English speakers than in native Chinese speakers. If reading skill is tightly related to activation in phonological processing regions this would suggest that acquisition of an orthography restructures the phonological awareness network in alphabetic languages.

MATERIALS AND METHODS

Participants

The current study included 62 participants (N = 62). Participants included Chinese-speaking adults (n = 16; ages 19–28 years; mean age = 21.50), Chinese-speaking children (n = 16; ages 8.50–12.30 years; mean age = 10.34), English-speaking adults (n = 15; ages 19–35 years; mean age = 22.70), and English-speaking children (n = 15; ages 8.00–12.60; mean age = 10.33).

The groups were controlled for age, gender, and accuracy/reaction time (RT) on the spoken word rhyming task (Table I). All participants met the following criteria: (1) native speakers of their language (English or Mandarin Chinese), (2) right-handed, (3) free of neurological disease or psychiatric disorders, (4) no attention deficit hyperactivity disorder, and (5) no learning disability. All children participants were given two standardized reading measures and were not included if they scored lower than one standard deviation below the mean on one or more standardized tests. Because the standardized tests in English and Chinese cannot be directly compared, behavioral data (i.e., accuracy and reaction time) from an experimental reading task comparable across languages was used to examine the relationship between skill activation in the phonological awareness network.

English-speaking participants were monolingual and had no exposure to Chinese. Chinese-speaking participants were only fluent in Chinese (Mandarin), but had some exposure to English in school. According to parental- or self-report, Chinese-speaking participants had low levels of fluency in speaking, reading, or writing English.

The Institutional Review Board at Northwestern University approved the informed consent procedures.

Tasks

During scanning, participants performed a rhyming judgment task to sequentially presented spoken word pairs (Fig. 1a) interspersed with perceptual control and fixation baseline trials. Pairs of word stimuli either rhymed or did not rhyme. Participants were asked to respond as quickly and as accurately as possible, using their right index finger for a yes (rhyme) response and their right middle finger for a no (nonrhyme) response. The duration of all words was between 500 and 800 ms, with the second word beginning 1,000 ms after the onset of the first. A red fixation cross appeared on the screen 1,000 ms after the onset of the second word, indicating the need to make a response. The response interval duration was variable (2,200, 2,600, or 2,800 ms), such that each trial lasted for either 4,000, 4,400, or 4,800 ms. Fixation baseline trials (24) were included as a baseline and required the participant to press the "yes" button when a fixation cross at the center of the screen turned from red to blue. Perceptual trials (24) were also included as part of a larger study, but were not of interest in the present experiment. These trials required participants to determine whether two sequentially presented tones matched or mismatched by pressing the "yes" or "no" button. The timing for the perceptual control and fixation baseline trials was the same as for the lexical trials.

In English, all words were monosyllabic without homophones. There were 24 trials in each of four conditions (Fig. 1b), and included two nonconflicting conditions, such that the words in each pair had similar orthographic and

TABLE I. Accuracy in percentages and reaction time (RT) in milliseconds on the auditory and the visual rhyming tasks

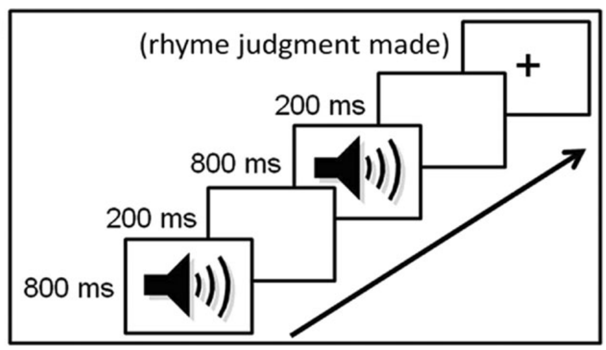
	Auditory rhyming conditions				
		Accuracy		RT	
	n	Nonconflicting	Conflicting	Nonconflicting	Conflicting
English					
Children	15	85% (9.4)	83% (9.9)	1,558 (224)	1,481 (192)
Adults	15	89% (6.3)	88% (6.7)	1,186 (224)	1,154 (198)
Chinese					
Children	16	81% (12.0)	76% (12.6)	1,680 (387)	1,648 (363)
Adults	16	93% (6.3)	88% (8.2)	1,092 (259)	1,149 (258)

The nonconflicting conditions included O+P+ and O−P−, whereas the conflicting conditions included O+P− and O−P+. Standard deviations are presented in parentheses. RT is reported for accurate trials only.

phonological endings (O+P+: e.g., gate–hate), or different orthographic and phonological endings (O-P-: e.g., press–list), and two conflicting conditions, such that words had similar orthographic but different phonological endings (O+P-, e.g., pint–mint), or different orthographic but similar phonological endings (O-P+, e.g., jazz–has). All words were matched across conditions for written word frequency in children [Zeno et al., 1996] and the sum of their written bigram frequency (English Lexicon Project; available at: http://elexicon.wustl.edu).

In Chinese, all words consisted of two characters without homophones. Disyllabic words were selected for Chinese because Chinese monosyllables have many homophones [Hoosain, 1991] that would be activated during spoken word processing [Chen and Juola, 1982; Hoosain and Osgood, 1983; Tan et al., 1996]. Therefore, using monosyllables for Chinese would make the rhyming task fundamentally different from English. As with the English stimuli, there were 24 trials in each of four conditions, two nonconflicting and two conflicting (Fig. 1b). Similar orthography was defined as sharing a phonetic radical for the second character of the word. The two nonconflicting conditions included one with similar orthography and phonology (O+P+, e.g. 端详/xiang2/, 汪洋/yang2/) and one with different orthography and phonology (O-P-, e.g. 损坏 /huai4/, 学科 /ke1/). The two conflicting conditions included one with similar orthography and different phonology (O+P-, e.g. 翻译 /yi4/, 选择 /ze2/) and another with different orthography and similar phonology (O-P+, e.g. 坚挺 /ting3/, 清醒 /xing3/). In half of the trials of the four lexical condition (rhyming and nonrhyming), the second character of the first and the second word had the same tone (e.g. 端详 /xiang2/, 汪洋 /yang2/), and in the other half they had different tones (e.g. 逮捕 /bu3/, 胸脯 /pu2/). Note that tonal information is controlled across conditions, so any condition differences are unlikely to be due to tonal information. The two-character words were matched on several variables across conditions including adult written number of strokes [Beijing Language and Culture University, 1999], word familiarity in third-graders, and word familiarity in fifth-graders. Word familiarity was assessed in an independent study on 50

a



b

Condition	Alphabetic (English)	Non-Alphabetic (Chinese)
Non-Conflicting	O + P + *gate, hate*	O + P + 端详 /xiang2/, 汪洋 /yang2/
Non-Conflicting	O – P – *press, list*	O – P – 损坏 /huai4/, 学科 /ke1/
Conflicting	O + P – *pint, mint*	O + P – 翻译 /yi4/, 选择 /ze2/
Conflicting	O – P + *jazz, has*	O – P + 坚挺 /ting3/, 清醒 /xing3/

Figure 1.

(**a**) Auditory rhyming task. Word pairs were presented in sequence in either English or Chinese. Note that the visual rhyming task (an independent measure of reading skill acquired outside of the MRI scanner) utilized the same design and timing parameters but words were visually presented. (**b**) Conflicting and nonconflicting conditions for English and Chinese. O+ indicates similar orthography (rime for English and phonetic radical for Chinese), O− indicates dissimilar orthography, P+ indicates similar phonology (rhymes), and P− indicates dissimilar phonology. The examples of the Chinese words include the pinyin pronunciation for the second character along with the tone indicated by 1–4.

third-graders and 50 fifth-graders using a 7-point scale. The second characters of words were also matched on adult written frequency [Beijing Language and Culture University, 1999] and number of strokes.

MRI Data Acquisition

Children were given a practice session in a scanner simulator. Different stimuli were used in the practice and scanning sessions. Participants lay in the scanner with their head position secured with foam padding. An optical response box was placed in the participant's dominant right hand and a compression alarm ball placed in the left hand. The head coil was positioned over the participant's head so that they could effectively use the mirror to view the projection screen at the rear of the scanner. All images were acquired using a 3.0T Siemens scanner (Siemens Healthcare, Erlangen, Germany). English-speaking participants were scanned at Northwestern University in Chicago and Chinese-speaking participants were scanned at Beijing Normal University. Gradient echo localizer images were acquired to determine the placement of the functional slices. For the functional images, a susceptibility weighted single-shot EPI (echo planar imaging) method with BOLD (blood oxygenation level-dependent) was used with the following scan parameters: TE = 20 ms, flip angle = 80°, matrix size = 128 × 128, field of view = 220, slice thickness = 3 mm (0.48 mm gap), number of slices = 33. These parameters resulted in a 1.7 × 1.7 × 3 mm voxel size. One hundred forty-five whole-brain volumes were acquired during each run using an interleaved bottom to top sequence, with one complete volume collected every 2 s (TR = 2,000 ms). A high resolution, T1-weighted three-dimensional image was also acquired with the following parameters: TR = 2,390 ms, TE = 2.9 ms, flip angle = 20° matrix size = 256 × 256, field of view = 256 mm, slice thickness = 1 mm, number of slices = 160. The acquisition of the anatomical scan took approximately 9 min.

Image Analysis

Data analysis was performed using SPM8 (available at: http://www.fil.ion.ucl.ac.uk/spm). The following steps were used for data preprocessing. (1) Slice timing correction for interleaved acquisition using sinc interpolation. (2) Fourth degree b-splice interpolation for realignment to the first volume. (3) Trilinear coregistration with the anatomical image. (4) Sixteen nonlinear iterations for normalization. (5) 4 × 4 × 8 mm full width half maximum Gaussian kernal smoothing. Up to two volumes where movement exceeded 4 mm in any of the x, y, or z dimensions were replaced with the mean of the images immediately before and after the outlying volume. Participants with >2 volumes with >4 mm of movement were excluded from the study. We normalized all brains to the standard T1 Montreal Neurological Institute (MNI) adult template, with a voxel size of $2 \times 2 \times 2$ mm^3 (12 linear affine parameters for brain size and position, 8 nonlinear iterations and $2 \times 2 \times 2$ nonlinear basis functions).

Statistical analyses at the first level were calculated using an event-related design with four lexical trial types, the perceptual control trials, and the fixation baseline trials as six conditions of interest. A high pass filter with a cutoff period of 128 s was applied. Trials were modeled using a canonical hemodynamic response function (HRF). Data from each subject were entered into a general linear model using an event-related analysis procedure. Group results were obtained using random-effects analyses by combining subject-specific summary statistics across the group as implemented in SPM8. The main effect of all lexical conditions versus the baseline fixation condition was tested using a one sample t-test separately for each age (children, adults) and separately for each language (Chinese, English). The coordinates from SPM were converted to MNI. The MNI coordinates were entered into the Talairach Client and the top matches for anatomical labels (brain regions and BA) were obtained. See Supporting Information Table I for a listing of all coordinates. We formed a union of these four maps ($P < 0.001$, >10 voxels) that served as a mask for all subsequent analyses to ensure that developmental effects were due to activation and not deactivation differences. In order to examine the interaction between age and language, we calculated the following contrast [(Chinese Children − Chinese Adults) − (English Adults − English Children)]. We did this for all lexical conditions minus the baseline fixation condition and for the conflicting (O−P+, O+P−) minus nonconflicting (O+P+, O−P−) conditions. In order to clarify any interaction effects, t-tests were calculated examining developmental effects within each language. Finally, in order examine the developmental effects of tone for Chinese, we calculated (Adults − Children) and (Children − Adults) contrasts for the different minus the same tone conditions.

In order to examine the relationship between reading skill and phonological processing in the brain, we extracted eigenvalues from the superior temporal gyrus based on the peak voxel in the significant interaction between age and language in this region for the contrast of all lexical conditions minus fixation baseline. Eigenvalues for each participant were extracted for a sphere with a 6 mm radius and we correlated this with the independent measure of reading skill—a parallel rhyming task to visually presented words performed outside of the scanner. This analysis was based on fewer subjects because three participants did not complete the visual rhyming task (two Chinese children and one English adult).

RESULTS

Behavioral Results

ANOVAs with age (children, adults), language (Chinese, English), and conditions (nonconflicting, conflicting) as factors were calculated on the auditory rhyming task separately for accuracy and reaction time (accurate trials only). Table I provides the accuracy in percentages and reaction time (RT) in milliseconds for the conflicting and the nonconflicting conditions for all four groups. Analysis of accuracy on these conditions revealed no significant interactions or main effect of age. There was a significant main effect of condition ($F_{(3,61)} = 14.053$, $P < 0.001$) with all groups achieving lower accuracies for conflicting conditions, and of language ($F_{(3,61)} = 14.124$, $P < 0.001$) with adults achieving higher accuracies than children. For reaction time, there was a significant interaction between condition and language ($F_{(3,61)} = 8.383$, $P < 0.005$). Within language post hoc tests reveal a main effect of condition only for English participants ($F_{(1,28)} = 9.647$, $P < 0.004$) with adults and children having faster RT for conflicting compared to nonconflicting conditions. There was also a significant main effect for age ($F_{(3,61)} = 42.335$, $P < 0.001$) showing that adults were faster than children. The behavioral analysis suggests that any differences in the developmental effects observed between languages should not be due to overall behavioral differences, as there was no interaction between age and language.

The visual rhyming task was completed outside of the scanner and represents a measure of reading skill. One English speaking and two Chinese speaking participants did not complete the visual rhyming task. Average accuracy and RT (standard deviations in parentheses) for English-speaking participants were 96% (3.7) and 965 ms (287) for adults, 85% (8.2) and 1,389 ms (251) for children. Average accuracy and RT for Chinese-speaking participants were 94% (2.6) and 1,077 ms (331) for adults and 77% (16.0) and 1,620 ms (302) for children. For accuracy on the visual rhyming task there was a significant main effect of age ($F_{(3,58)} = 31.606$, $P < 0.001$) with adults achieving higher accuracies than children, but the effect of language and the interaction term were not significant. For reaction time, there was a significant main effect of age ($F_{(3,58)} = 77.129$, $P < 0.001$) and language ($F_{(3,58)} = 8.729$, $P < 0.05$) but the interaction was not significant. The main effects show that adults were faster than children and English speakers were faster than Chinese speakers.

fMRI Results

In reporting the fMRI results, we will focus on effects that showed an interaction between age (children, adults) and language (Chinese, English). In the contrast of all lexical conditions compared to fixation baseline, we found an interaction for left IPL/supramarginal gyrus (BA 40), left superior parietal lobule (BA 7), left STG (BA 22, 42), right middle temporal gyrus (BA 22), bilateral ventral IFG (BA 46, 47), and left dorsal IFG (BA 45) (Fig. 2). Table II provides the regions significant for an interaction between age (children, adults) and language (Chinese, English) for the contrast of all lexical conditions compared with fixation baseline. The interaction in these regions was due to greater developmental increases in English compared with Chinese. Children showed greater activation than adults in a variety of regions for both English and Chinese, but this did not seem to drive the interaction with language. The main effects for the lexical conditions versus baseline for each group can be found as Supporting Information Table I and Supporting Information Figures 1 and 2.

In the contrast of the conflicting (O−P+, O+P−) compared with the nonconflicting conditions (O+P+, O−P−there was an interaction between age and language for left STG (BA 22) (Fig. 3). Table III provides a list of the regions significant for an interaction between age (children, adults) and language (Chinese, English) for the contrast of the conflicting compared with the nonconflicting conditions. The interaction in the STG was due to greater developmental increases in English compared with Chinese. This increase in the STG for the English was greater for the conflicting compared with the nonconflicting conditions.

The tone analysis for Chinese revealed no significant developmental differences when comparing the different with the same tones. These results are consistent with behavioral investigations of tone awareness in Chinese suggesting that this is an early developing skill that matures to near adult levels before children begin attending school [Xu et al., 2004].

In order to determine if the activation in left STG was related to reading skill, we extracted eigenvalues (for the contrast of the all lexical conditions compared with fixation baseline) in this region during the rhyming task to spoken words and correlated this with an independent measure of visual word processing (a parallel rhyming task outside of the MRI scanner). Higher skill was positively correlated with greater activation in this region for English children ($r_{(15)} = 0.590$, $P < 0.021$), but not for any other group (Fig. 4).

DISCUSSION

Although there have been extensive studies on the neural basis of reading acquisition [Ben-Shachar et al., 2011; Bitan et al., 2006, 2007, 2008; Booth et al., 2003, 2004, 2007; Brem et al., 2010; Brown et al., 2005; Cao et al., 2009; Dehaene et al., 2010; Hoeft et al., 2011; Parviainen et al., 2006; Schlaggar and McCandliss, 2007; Shaywitz, 2002; Turkeltaub et al., 2003], there are relatively few studies on the neural basis of spoken language development [Brauer et al., 2008; Cao et al., 2011; Cone et al., 2008; Schild et al., 2011]. We extended two previous studies on spoken language [Cao et al., 2011; Cone et al., 2008] by including a larger age range to more effectively establish developmental differences in phonological processing. Previous experiments have examined developmental differences in English and Chinese in separate studies, so any conclusions of cross-linguistic differences are speculative. By directly comparing developmental differences in English

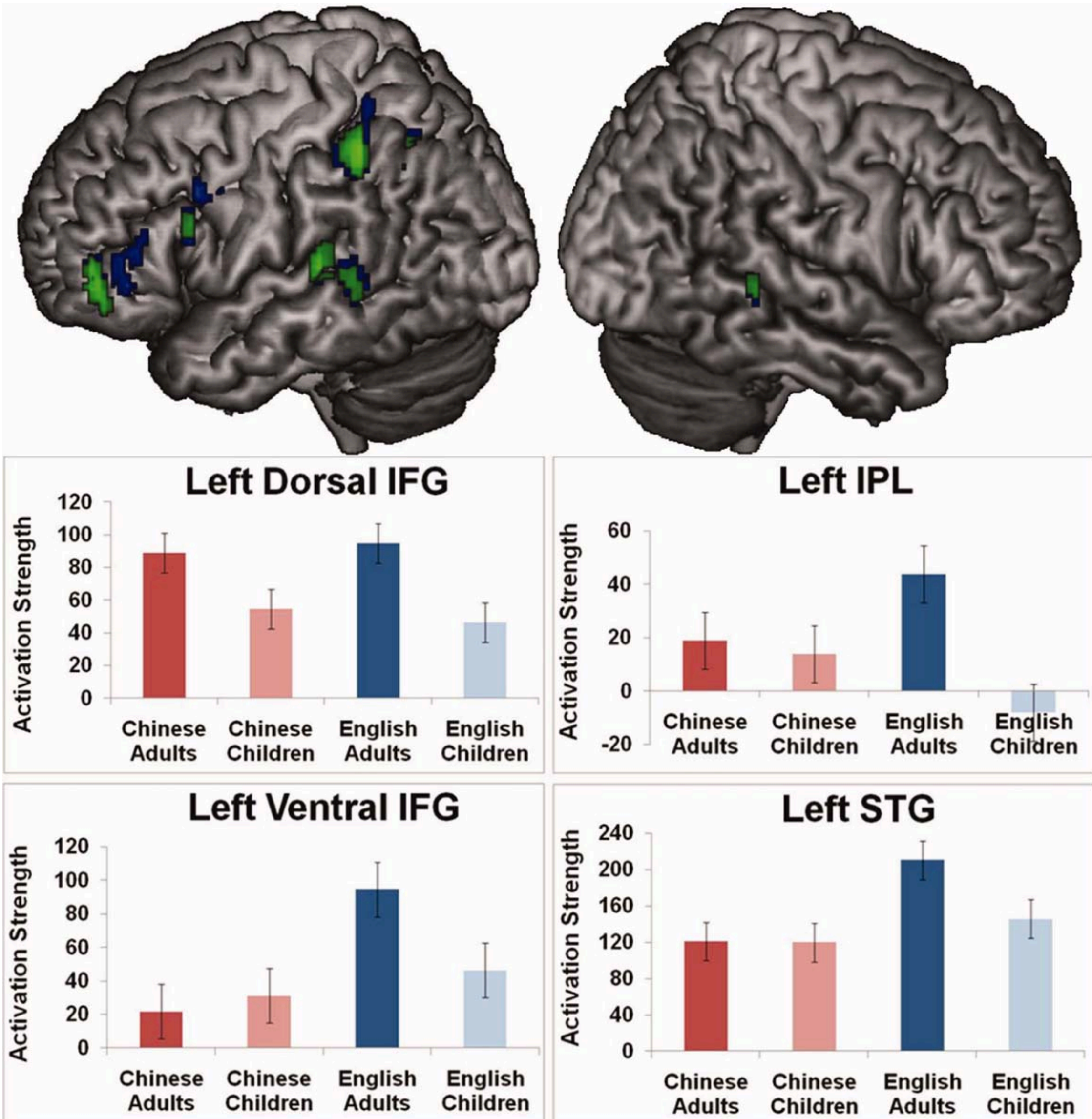


Figure 2.

Interaction between age (children, adults) and language (Chinese, English) for the auditory rhyming task for all the lexical conditions compared with fixation baseline. Legend: green: interaction overlapping with the developmental increase for English; blue: developmental increase in English. A significant interaction was found in the left dorsal inferior frontal gyrus (IFG), left ventral IFG, left inferior parietal lobule (IPL), and left superior temporal gyrus (STG). The bar charts illustrate the activation strength (eigenvalues extracted from 6 mm sphere around the peak voxel in the interaction term) for each region for each of the four groups. These charts clearly show larger developmental increases for English compared with Chinese. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

versus Chinese, we can more definitively address whether the nature of the orthographic system changes the nature of phonological processing. Our study suggests that extensive experience with an alphabetic orthographic system restructures the phonological network because of the semi-regular relationship at the level of very small units (i.e., letters and sounds). Alphabetic orthographies may specifically enhance the smallest graphemic units (i.e., letters) and foster reorganization of phonological representations at the level of the phoneme. Because Chinese characters map to spoken syllables, there appears to be a weaker influence of orthography on phonological processing. Acquisition of reading skill in Chinese may also have a limited influence on spoken language processing due to

TABLE II. Interaction between age (children, adults) and language (Chinese, English) for the contrast of all lexical conditions compared with fixation baseline

Contrast	Region	H	BA	Voxels	z-Value	x	y	z
Interaction								
	Inferior parietal lobule	L	40	90	4.65[a]	−48	−44	48
	Supramarginal gyrus	L	40	—	3.67[a]	−38	−44	36
	Superior parietal lobule	L	7	52	4.5[a]	−28	−60	44
	Superior temporal gyrus	L	42	38	4.4	−64	−30	12
	Inferior frontal gyrus	L	46	41	4.26[a]	−48	46	0
	Thalamus	R	n/a	13	3.98	18	−26	−2
	Inferior frontal gyrus	L	45	20	3.69	−52	14	24
	Middle temporal gyrus	R	22	12	3.62	56	−38	2
	Inferior frontal gyrus	R	47	22	3.55	30	26	−2
	Superior temporal gyrus	L	22	29	3.55[a]	−62	−42	8
	Superior temporal gyrus	L	22	—	3.42[a]	−54	−38	8
English adults > children								
	Inferior parietal lobule	L	40	182	4.87[a]	−48	−44	48
	Supramarginal gyrus	L	40	—	3.88[a]	−38	−44	36
	Postcentral gyrus	L	5	—	3.41[a]	−40	−48	62
	Superior parietal lobule	L	7	67	4.73[a]	−28	−60	44
	Superior temporal gyrus	L	42	46	4.62[a]	−64	−30	12
	Superior temporal gyrus	L	42	—	3.29[a]	−58	−30	6
	Inferior frontal gyrus	L	46	53	4.35[a]	−48	46	2
	Inferior frontal gyrus	L	45	40	4.12[a]	−52	14	24
	Superior temporal gyrus	L	22	89	3.96[a]	−62	−42	8
	Middle temporal gyrus	L	22	—	3.75[a]	−54	−38	8
	Superior temporal gyrus	L	42	—	3.23[a]	−46	−42	6
	Inferior frontal gyrus	L	46	70	3.9[a]	−40	32	8
	Middle frontal gyrus	L	47	—	3.71[a]	−44	36	0
	Inferior frontal gyrus	L	46	—	3.47[a]	−48	40	8
	Middle frontal gyrus	L	9	38	3.86[a]	−48	12	34
	Inferior frontal gyrus	L	9	—	3.48[a]	−42	6	30
	Middle temporal gyrus	R	21	21	3.85	56	−38	2
	Inferior frontal gyrus	R	47	38	3.72[a]	30	26	−2
English children > adults								
	Thalamus	R	n/a	22	4.26	18	−26	−2
	Thalamus	L	n/a	11	3.93	−24	−32	28
	Insula	R	13	24	3.88	36	14	6
	Insula	L	13	15	3.86	−26	−94	6
	Middle occipital gyrus	L	18	11	3.52	−38	−10	24
Chinese adults > children								
	No suprathreshold clusters							
Chinese children > adults								
	Superior temporal gyrus	R	22	27	3.89	52	10	−2
	Superior temporal gyrus	L	22	27	3.89	−46	8	−2
	Insula	L	13	13	3.78	−36	14	−2
	Middle occipital gyrus	L	19	19	3.63	−44	−80	2
	Cingulate gyrus	R	32	15	3.57	8	20	34
	Culmen	R	n/a	10	3.45	8	−52	−2
	Fusiform gyrus	R	19	10	3.32	24	−58	−12

Developmental effects within each language are also presented. Peaks are presented at a threshold of $P < 0.001$ uncorrected, 10, or greater voxels. — indicates subpeaks within a given cluster.
[a]Region was significant at a clusterwise threshold of $P < 0.05$ corrected for multiple comparisons.

a one-to-many mapping between phonology and orthography (i.e. the same spoken syllable can refer to multiple characters).

Our finding of a developmental increase in the influence of orthographic representations on phonological processing for English (left IFG, STG, IPL) is consistent with previous behavioral and imaging studies in alphabetic languages. Behavioral studies show that alphabetic orthographic representations in adults influence spoken word processing [Perre and Ziegler, 2008; Ziegler and Ferrand, 1998] and that

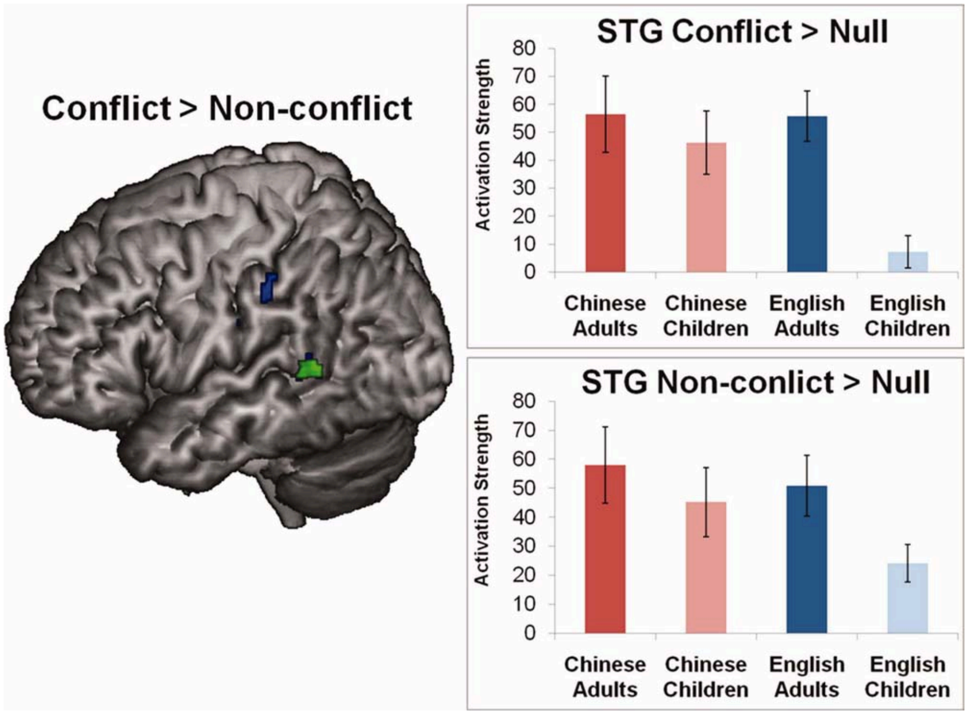


Figure 3.

Interaction between age (children, adults) and language (Chinese, English) for the auditory rhyming task for the conflicting compared with the nonconflicting conditions. Legend: green: interaction overlapping with the developmental increase for English; blue: developmental increase in English. A significant interaction was found in the left superior temporal gyrus (STG). The bar graphs illustrate the activation strength (eigenvalues extracted from 6 mm sphere around the peak voxel in the interaction term) for the conflicting (top panel) and the nonconflicting (bottom panel) compared with fixation baseline for each of the four groups. These charts clearly show larger developmental increases in the conflict effect for English compared with Chinese. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

orthographic knowledge in children is a strong predictor of later phonological awareness [Wagner et al., 1997]. Neuroimaging studies in adults have also shown an influence of orthographic manipulation during spoken language processing tasks in the phonological network using fMRI [Booth et al., 2002], ERP [Perre and Pattamadilok, 2009] and TMS [Pattamadilok et al., 2010]. Moreover, greater orthographic effects in English have been shown in older compared to younger children [Cone et al., 2008], in typical children compared with those with reading disability [Desroches et al., 2010], and in literates compared to illiterates [Dehaene, 2010]. Although behavioral research suggests weaker orthographic effects on spoken language processing in Chinese [De Gelder and Vroomen, 1992], there is little evidence regarding developmental or skill based orthographic effects on oral language processing [Cao et al., 2011]. We found greater developmental increases for English in recruitment of brain regions involved in phonological processing; suggesting that acquisition of an alphabetic, but not a logographic, writing system reorganizes the phonological awareness network in the brain.

Phonological representations in English may reorganize as alphabetic experience enhances sensitivity to smaller orthographic grain sizes. We found developmental increases in the activation of STG for English but not Chinese. This increase was even more pronounced for word pairs with conflicting orthography and phonology (e.g. pint-mint, jazz-has) as compared with nonconflicting pairs. Moreover, we showed that higher reading skill was correlated with greater activation of STG for English but not Chinese. Previous studies demonstrate that experience with an alphabetic system enhances the ability to manipulate spoken language at the level of the phoneme, suggesting that sensitivity for small grain sizes increases distinctly when learning an alphabetic system [Morais et al., 1979; Read et al., 1986; Schild et al., 2011]. For example, children with alphabetic reading skills had greater fidelity of neural responses to spoken words when doing a word onset priming task requiring sensitivity to phonemes when compared with children who were prereaders or beginning readers [Schild et al., 2011]. In addition, illiterates were unable to perform phoneme addition and deletion tasks in contrast to individuals given basic alphabetic reading instruction [Morais et al., 1979]. Moreover, Chinese-speaking adults who were literate in both characters and alphabetic spelling (pinyin) performed accurately on phonemic

TABLE III. Interaction between age (children, adults) and language (Chinese, English) for the contrast of the conflicting compared with the nonconflicting conditions

Contrast	Region	H	BA	Voxels	z-Value	x	y	z
Interaction								
	Superior temporal gyrus	L	22	60	4.32[a]	−48	−44	8
	Superior temporal gyrus	L	22	—	4.15[a]	−50	−52	8
	Superior temporal gyrus	L	22	—	3.54[a]	−56	−48	12
English adults > English children								
	Insula	L	13	15	4.41	−46	−22	24
	Superior temporal gyrus	L	22	56	4.27[a]	−48	−44	8
	Superior temporal gyrus	L	22	—	4.08[a]	−50	−52	8
	Superior temporal gyrus	L	22	—	3.65[a]	−56	−48	12
	Inferior parietal lobule	L	40	12	4.25	−52	−32	42
	Thalamus	L	n/a	12	4.09	−8	−22	0
English children > English adults								
	No suprathreshold clusters							
Chinese adults > Chinese children								
	No suprathreshold clusters							
Chinese children > Chinese adults								
	No suprathreshold clusters							

Developmental effects within each language are also presented. Peaks are presented at a threshold of $P < 0.001$ uncorrected, 10 or greater voxels. — indicates subpeaks within a given cluster.
[a]Region was significant at a clusterwise threshold of $P < 0.05$ corrected for multiple comparisons.

segmentation tasks, whereas those trained to read Mandarin characters showed an inability to perform phonemic segmentation tasks [Read et al., 1986]. These previous investigations combined with the current results suggest that phonological awareness is uniquely shaped by exposure to and training of an orthography that has systematic mappings between letters and phonemes (i.e., alphabetic orthographies), enhancing sensitivity to small units including letters and phonemes.

Our behavioral results support the effect of orthographic representations on spoken language processing as words with conflicting orthography and phonology were less accurate than words with nonconflicting information. In contrast to the accuracy analyses, we did not find evidence for an overall conflict effect in reaction times, but rather we showed an interaction between language and conflict. Consistent with our brain imaging analyses, Chinese speakers did not show a reliable conflict effect. However,

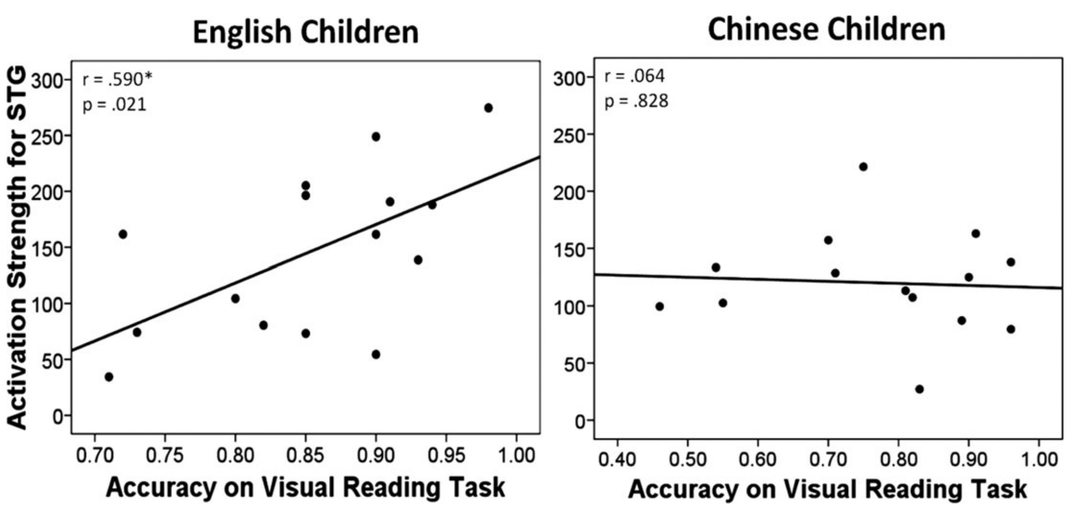


Figure 4.
A significant positive correlation was found for English but not Chinese children between activation in the superior temporal gyrus (STG) during the spoken word rhyming task and reading skill (based on a rhyming task to visually presented words outside of the MRI scanner).

the English speakers were reliably faster at processing conflicting compared with nonconflicting pairs. The main neuroimaging finding of our study is that English speakers, especially adults, showed greater activation for conflicting compared with nonconflicting items. This finding could not be accounted for time on task because the English speakers were actually faster at the conflicting pairs, although the interpretation of this behavioral advantage is not clear.

The current study used an oral language task that required the listener to segment the onset and then make a determination of whether two words rhyme. This task therefore required sensitivity to grain sizes smaller than the syllable. Chinese is a tonal language and may therefore foster greater sensitivity to supra-segmental information that spans the syllable. There is evidence that suggests experience with a tonal language may influence the development of the oral language network. Indeed, several lines of research that involved the manipulation of tone processing suggest that Chinese speakers have greater subcortical and cortical sensitivity to tonal information. Greater fidelity of brainstem encoding of tonal changes [Krishnan and Gandour, 2009; Krishnan et al., 2005, 2008, 2010; Swaminathan et al., 2008] and greater cortical ERP mismatch negativity sensitivity to tonal information has been reported when Chinese speakers were compared to English speakers [Chandrasekaran et al., 2009a,b; Kaan et al., 2007]. Unlike the ERP pattern elicited from English speakers showing sensitivity for phonemes [Desroches et al., 2009], ERP patterns for Chinese speakers revealed differences for mismatched words at the level of the syllable [Zhao et al., 2011]. Neuroimaging studies have also shown differences in Chinese compared with English speakers in the oral language network when processing tonal information [Gandour et al., 2003, 2004; Hsieh et al., 2001; Klein et al., 2001]. While previous investigations focused on tone processing, the current study focused on rhyming while controlling for variations in tone. Additionally, a within language (Chinese) developmental comparison of same and different tone revealed no significant interaction in the current study, which may be due to the fact that tone sensitivity emerges early [Xu et al., 2004]. The current results in combination with previous investigations of tone processing, suggest that sensitivity to supra-segmental information is enhanced in Chinese due to an emphasis on discrimination of tonal contours, whereas sensitivity to discrete phonemes is emphasized and thus enhanced in alphabetic systems.

Given that the current study included stimuli with different numbers of syllables in English and Chinese, it would be informative to conduct a study that equated syllables across languages. However, it is likely that the results would be similar because greater developmental increases were seen in English than in Chinese for activation in the superior temporal gyrus when comparing the conflicting with the nonconflicting conditions. If the cross-linguistic results were driven by word structure differences, we would expect no effects of condition, unless of course there was an interaction between age, language, condition, and word structure. It is unlikely that differences in the number of syllables confounded our findings of cross-linguistic developmental differences because syllable awareness is early developing in both Chinese and English [Liberman et al., 1974; McBride-Chang et al., 2008; Shu et al., 2008].

While acquisition of phoneme awareness may arise as alphabetic orthographic experience increases, restructuring of the phonological system could also result from associations between larger orthographic and phonological grain sizes [Taft, 2006; Taft and Hambly, 1985]. In this case, experience with Chinese orthography may also result in changes to phonological representations. The current study presents no evidence that this is the case, although this may be due to the type of task selected. Perhaps a phonological awareness task that emphasized larger phonological units (such as syllables) would yield evidence that experience with Chinese orthography also influences phonological awareness networks.

While the current study included a rhyming task, previous investigations have found evidence of orthographic involvement in spoken language for alphabetic languages using several different types of phonological and nonphonological tasks, such as phoneme monitoring [Dijkstra et al., 1995], phoneme counting [Treiman and Cassar, 1997], phoneme deletion and reversal [Castles et al., 2003], word generation of phonologically similar words [Muneaux and Ziegler, 2004], lexical decision [Che'reau et al., 2007; Jakimik et al., 1985; Ziegler and Ferrand, 1998], semantic categorization and grammatical gender categorization (Peereman et al., 2009], and lexical decision combined with immediate word repetition [Ventura et al., 2004]. A cross task comparison of three different spoken word tasks (rhyming, lexical decision, and word repetition) conducted by Ziegler et al. [2004] with a manipulation of the degree of spelling inconsistency found that inconsistent words with subdominant spellings were processed more slowly than inconsistent words with dominant spellings in all three tasks, with the strongest effect for lexical decision, an intermediate effect in rhyming, and the weakest effect in word repetition. The authors draw two critical conclusions from their data: first, that orthographic consistency effects are not artifacts of the phonological properties of the stimuli; second, orthographic effects are seen across multiple type of tasks, not just metaphonological tasks. In contrast, recent ERPs studies that directly investigated the influence of orthographic knowledge on speech processing suggest that the mechanisms underlying the occurrence of the orthographic effects may vary with task demands [Pattamadilok et al., 2009, 2011]. The present findings suggest that extensive experience with an alphabetic orthography restructures the neural mechanisms for phonological processing. It is currently unknown if these influences extend to other types of speech recognition tasks that do not require an explicit analysis of the phonological information.

Connectionist models provide insight into how phonological representations are changed as a result of acquiring an alphabetic compared with a nonalphabetic orthography. These models assume that cognitive processes such as reading arise from the activity of a network of neurons, and simulate these processes by analogy through activation of a network of interconnected computational processing units. The weights of the connections between processing units encode information, and thus these models learn through a gradual modification of these weights during training. Connectionist models are extremely sensitive to the training environment, which includes the model's parameters such as learning rate and the training corpus. Because investigators can precisely control the learning environment, computational models are an ideal tool for studying how experience with verbal and written language influences linguistic representations.

Harm and Seidenberg [1999] implemented a connectionist model that they initially trained on phonology. In this early learning state, the model encoded the sort of phonological knowledge gained during early exposure to verbal language. The model was later trained to map from orthographic to phonological representations, which simulated later reading instruction. Comparisons between the literate and illiterate network found that weights among phonological units in the literate network were larger indicating that it had developed stronger attractor basins. Attractor basins act like points with high gravitational pull in representational space, and will emerge for frequently encountered separable patterns in the training corpus (e.g., prototypical representations of phonemes such as /ba/ and /ga/), but not for patterns that are rarely encountered (e.g., for illegal phonemic patterns). Thus, fuzzy phonological representations "fall into" these attractor basins by virtue of being "close enough." The formation of these phonological attractor basins resulted in better performance on feature and segmentation restoration tasks and also enhanced the representation of the rime. Furthermore, rhyming words were more similar in their phonological representations in the literate network compared with the nonliterate network. It is possible that the training induced changes in the model correspond to the developmental and reading skill related increases in activation we see in phonological processing regions for our English speakers. In fact, evidence from several studies of reading development in English demonstrate that high skill in reading correlates with high skill in phonology-related tasks [Stahl and Murray, 1994; Wagner and Torgesen, 1987], suggesting that the model's training results in performance that mirrors people's training.

Yang et al. [2009] recently applied this connectionist model to learning to read in Chinese. As with the Harm and Seidenberg [1999] model, mapping between orthographic and phonological representational units was achieved by a layer of hidden units, which serves as a convergence zone [Bitan et al., 2005] between these networks. Compared with models trained on English, Chinese models required more hidden units to accommodate the greater number of arbitrary relations because regularities within the orthography-to-phonology mappings in English capture these redundancies with similar patterns of activation over the same sets of mapping units. Moreover, activation within hidden units in the Chinese model was sparser, which the authors attributed to encoding of a greater range of possible inputs with fewer sublexical regularities in Chinese than in English. All else being equal, each active unit in a sparse representation has a proportionally greater influence on the final phonological representation than those in a diffuse distributed representation. Despite being individually more influential on phonology, sparsely activated hidden units may activate phonology to an equivalent (or even lesser) degree than those in diffuse representations. Moreover, the greater weight implied by sparse activations is a double-edged sword: errors among sparse hidden representations introduce proportionally larger errors into phonological representations. The sublexical regularities encoded among hidden representations in Harm and Seidenberg's model of English [1999] introduce additional constraints on phonological output representations, and act as an error-correction mechanism by restricting phonological output patterns to those legal within the language. Because hidden unit representations in Chinese do not encode sublexical regularities and may introduce larger errors in phonological representations, activation in the Chinese phonological network may be less robust, and more dependent on influence from other systems (e.g., semantics). These connectionist models thus provide an explanation for the greater developmental and reading skill increases in phonological processing regions observed for the English speakers as compared with the Chinese speakers in our study.

Although there was not a significant interaction between language and age associated with developmental changes in Chinese, when examining each group separately, we found developmental decreases in activation of the left middle occipital gyrus and fusiform gyrus for Chinese only. Behavioral research suggests a weaker orthographic effect on spoken language processing in Chinese [Zhou and Marslen-Wilson, 1999] and a recent fMRI study found a developmental reduction in the involvement of orthography in spoken word processing in Chinese [Cao et al., 2011]. The one-to-many mapping from phonology to orthography for larger units (i.e., syllables) in Chinese may create orthographic interference on auditory rhyming judgments. Chinese speaking adults may be sensitive to this interference and show less orthographic activation in our auditory rhyming task as compared with children. In contrast, neuroimaging studies in English have shown activation in orthographic processing regions during spoken language processing in adults using fMRI [Booth et al., 2002], ERP [Perre and Pattamadilok, 2009], and TMS [Pattamadilok et al., 2010]. Alphabetic speakers have also been found to have greater activation of orthographic regions during oral language processing with increased skill and experience [Desroches et al., 2010; Castro-Caldas et al., 1998; Cone et al., 2008]. Our study taken together with previous research suggests that experience with a writing system with a one-to-many mapping for large units between phonology and orthography (i.e., Chinese) results in decreased involvement of orthography whereas experience with a writing system with a more systematic relationship between small units (i.e., English) results in increased involvement of orthography during oral language processing.

In conclusion, the current study shows that learning to read an orthography restructures the phonological processing network in the brain more for alphabetic compared with nonalphabetic orthographies. This is likely due to differences in the nature of mapping between orthography and phonology in the two languages. English has a relatively systematic mapping at smaller grain sizes of letters to phonemes, whereas Chinese has relatively arbitrary mapping at larger grain sizes from character to syllable. The changes in the spoken word processing network for English speakers may be the neural correlate of better phonological awareness skills we see in alphabetic languages.

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